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Tectonic speed limits from plate kinematic reconstructions

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Abstract

The motion of plates and continents on the planet's surface are a manifestation of long-term mantle convection and plate tectonics. Present-day plate velocities provide a snapshot of this ongoing process, and have been used to infer controlling factors on the speeds of plates and continents. However, present-day velocities do not capture plate behaviour over geologically representative periods of time. To address this shortcoming, we use a plate tectonic reconstruction approach to extract time-dependent plate velocities and geometries from which root mean square (RMS) velocities are computed, resulting in a median RMS plate speed of ∼4 cm/yr∼4 cm/yr over 200 Myr. Linking tectonothermal ages of continental lithosphere to the RMS plate velocity analysis, we find that the increasing portions of plate area composed of continental and/or cratonic lithosphere significantly reduces plate speeds. Plates with any cratonic portion have a median RMS velocity of ∼5.8 cm/yr∼5.8 cm/yr, while plates with more than 25% of cratonic area have a median RMS speed of ∼2.8 cm/yr∼2.8 cm/yr. The fastest plates (∼8.5 cm/yr∼8.5 cm/yr RMS speed) have little continental fraction and tend to be bounded by subduction zones, while the slowest plates (∼2.6-2.8 cm/yr∼2.6-2.8 cm/yr RMS speed) have large continental fractions and usually have little to no subducting part of plate perimeter. More generally, oceanic plates tend to move 2-3 times faster than continental plates, consistent with predictions of numerical models of mantle convection. The slower motion of continental plates is compatible with deep keels impinging on asthenospheric flow and increasing shear traction, thus anchoring the plate in the more viscous mantle transition zone. We also find that short-lived (up to ∼10 Myr∼10 Myr) rapid accelerations of Africa (∼100 and 65 Ma), North America (∼100 and 55 Ma) and India (∼130,80 and 65 Ma∼130,80 and 65 Ma) appear to be correlated with plume head arrivals as recorded by large igneous province (LIPs) emplacement. By evaluating factors influencing plate speeds over the Mesozoic and Cenozoic, our temporal analysis reveals simple principles that can guide the construction and evaluation of absolute plate motion models for times before the Cretaceous in the absence of hotspot tracks and seafloor spreading histories. Based on the post-Pangea plate motions, one principle that can be applied to pre-Pangea times is that plates with less than ∼50%∼50% continental area can reach RMS velocities of ∼20 cm/yr∼20 cm/yr, while plates with more than 50% continental fraction do not exceed RMS velocities of ∼10 cm/yr∼10 cm/yr. Similarly, plates with large portions of continental or cratonic area with RMS velocities exceeding ∼15 cm/yr∼15 cm/yr for more than ∼10 Myr∼10 Myr should be considered as potential artefacts requiring further justification of plate driving forces in such scenarios.

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Tectonic speed limits from plate kinematic reconstructions

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Highlights

- We use plate reconstructions to evaluate continental effects on plate velocities
- Increasing portion of continental plate area slows down plate motions
- Both Proterozoic and Archean cratons impede fast plate motions
- Continental plate accelerations linked to plume head arrivals
- Continental keels likely increase plate-mantle coupling

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Abstract

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(LIPs) emplacement. By evaluating factors influencing plate speeds over the Mesozoic and Cenozoic, our temporal analysis reveals simple principles that can guide the construction and evaluation of absolute plate motion models for times before the Cretaceous in the absence of hotspot tracks and seafloor spreading histories. Based on the post-Pangea plate motions, one principle that can be applied to pre-Pangea times is that plates with less than ~50% continental area can reach RMS velocities of ~20 cm/yr, while plates with more than 50% continental fraction do not exceed RMS velocities of ~10 cm/yr. Similarly, plates with large portions of continental or cratonic area with RMS velocities exceeding ~15 cm/yr for more than ~10 Myr should be considered as potential artefacts requiring further justification of plate driving forces in such scenarios.

Keywords: RMS plate velocities, plate reconstructions, continent and craton speeds

1. Introduction

The configuration and motion of plates on Earth's surface is an intrinsic manifestation of plate-mantle coupling and of the evolving heat engine of our planet's interior. The complex interaction of plate boundary forces results in plate motions dictated by the dominance of slab pull and ridge push forces (Forsyth and Uyeda, 1975), as well as the effects of mantle drag (Conrad and Lithgow-Bertelloni, 2006) and radial viscosity contrasts (Phillips and Bunge, 2005). The accurate present-day measurement of plate velocities (Fig. 1A) relies on satellite observations (especially useful for deforming regions), and is supplemented by young oceanic magnetic anomaly identifications and continental Quaternary fault offsets (DeMets et al., 2010; Kreemer et al., 2014). Plate velocities in the geological past rely on well-constrained relative plate motions from magnetic anomaly identifications, as well as plate circuits that link relative plate motions to an absolute reference frame (see Torsvik et al., 2008). However, plate reconstructions using seafloor magnetic anomaly identifications extend only to the time of Pangea, as very little in-situ oceanic lithosphere is preserved from earlier times. To take advantage of the post-Pangea seafloor spreading record, we use a plate reconstruction approach to evaluate factors affecting the speed of plate motions, including the effects of continents, cratons, subduction zones and plume head arrivals in the Mesozoic and Cenozoic. Although ridge push is an important plate boundary force, it is largely secondary to the dominant slab pull (Forsyth and Uyeda, 1975), and for this reason we do not investigate the role of effective ridge lengths in this study.

We harness decades of data collection and identification of seafloor magnetic anomalies, and their incorporation into global plate reconstructions (Seton et al., 2012) that capture plate motions and plate boundary evolution. We test the findings of Stoddard and Abbott (1996) that Archean lithosphere impedes plate motions, while Proterozoic lithosphere promotes higher plate velocities in a time-dependent plate reconstruction context. Using the global plate reconstruction approach, we are able to extract statistics for the last 200 Myr, increasing the sample size from a handful of plates at present-day to 85 distinct plates over the post-Pangea timeframe, resulting in a total 3,952 samples of plate behaviour. Our results not only have first-order implications for our understanding of plate tectonics, but can guide the construction and evaluation of pre-Pangea plate motion models (e.g., Domeier and Torsvik, 2014) for which no in-situ oceanic lithosphere is preserved, thus requiring the creation of synthetic plates from geological proxies.

1.1 Plate velocities from plate reconstructions

A number of key studies have investigated the factors affecting plate velocities, including the modulating effects of plate, continental and cratonic areas (Gordon and Jurdy, 1986; Solomon et al., 1977; Stoddard and Abbott, 1996). These early studies were limited by the sample size of plate speed measurements – for example, present-day plate velocities from eight plates (Australia was deemed an outlier) were analysed by Stoddard and Abbott (1996) who suggested that deep Archean keels result in slower-moving plates while conversely suggesting that Proterozoic lithosphere likely had a positive feedback on plate velocities.

The general approach of using present-day data alone would be sufficient assuming that the instantaneous plate configurations and velocities are representative of Phanerozoic and older plate tectonics. It is therefore essential to incorporate post-Pangea plate tectonic reconstructions to capture plate behaviour over a geologically representative period of time that is constrained largely by seafloor spreading histories. Solomon et al. (1977) pioneered such an approach, and analysed global plate velocities for the present-day and a single plate reconstruction at 55 Ma, which captured the very fast northward motion of India towards Eurasia. The convergence between India and Eurasia is ~5 cm/yr at present, while at ~55 Ma was up to 19 cm/yr (Zahirovic et al., 2012), highlighting the contrast between recent and past plate velocities. A similar approach with increased temporal resolution using six stages bounded by 56, 48, 43, 25, 10 and 0 Ma was incorporated by Gordon and Jurdy (1986), whose results suggested that oceanic plates move faster than continental plates.

Similarly, Schult and Gordon (1984) applied a time-dependent approach and computed the root mean square (RMS) velocities for continental blocks at 180, 144, 123, 83, 48 and 37 Ma to find that continents have moved faster in the past, and that oceanic plates have higher RMS velocities than continental plates. Although Schult and Gordon (1984) find that continental area and RMS plate velocities are inversely correlated, their results suggested that continental keels were unlikely to greatly resist plate motions because some continental plates (e.g., India) had moved more rapidly in the past. However, the small number of time-steps resulted in averaging over long time intervals where plate motions may have changed rapidly, such as rapid accelerations and decelerations of India (van Hinsbergen et al., 2011b), as well as major plate reorganizations over a few million years (Matthews et al., 2012).

1.2 Cratons and their effect on plate velocities

An early review of the continental tectosphere by Jordan (1975) established, from seismic wave experiments and heat flow modelling, that continental keels protrude several hundred kilometres into the convecting mantle. In the same year, Forsyth and Uyeda (1975) quantified forces acting on tectonic plates, concluding that continents impede plate motion likely because of the higher viscosities beneath them and their possible anchoring role. However, it has been difficult to consistently map and characterise lithospheric thicknesses globally to isolate the effect of cratonic keels on plate velocities. A self-consistent approach using S-wave seismic tomography was used by Abbott et al. (2000) to map global seismic lithospheric thicknesses, and thus characterise cratonic lithosphere using seismic velocity anomalies with a thermal correction applied to account for lateral variations in asthenosphere temperature. The resulting 5°×5° grid of lithospheric thicknesses had lower resolutions for South America and Africa, and generally half the ray coverage for the southern hemisphere compared to the northern hemisphere (Abbott et al., 2000). An alternative approach was used by Artemieva (2006) who used heat flow data alone, and argued that seismic lithospheric thicknesses do not take into account compositional heterogeneities, which can account for up to 50% of the seismic velocity anomaly. The tectonothermal ages were used to interpolate for regions with low density of heat flow measurements in order to produce a 1°×1° global grid (Artemieva, 2006). However, similar to the drawbacks of using purely seismic tomography interpretations, the tectonothermal approach also had significant uncertainties for Antarctica.

2. Methods

We analyse a modified version of the Seton et al. (2012) plate motion model (included as Supplement), and extract evolving plate topologies following Gurnis et al. (2012) in 1 Myr intervals using the open-source and cross-platform plate reconstruction software, GPlates (www.gplates.org). Stage rotations and plate velocities are also interpolated at 1 Myr intervals (Fig. 1B, 2) to capture the inherited motions of the entire plate circuit, and plate reorganizations occurring over short geological intervals with abrupt inception and abandonment of major plate boundaries.

The plate motion model utilises a moving Indo-Atlantic hotspot reference frame (O'Neill et al., 2005) for times since 100 Ma, and a True Polar Wander-corrected paleomagnetic reference frame (Steinberger and Torsvik, 2008) for earlier times. We test the effects of alternative absolute reference frames on global RMS velocities by comparing fixed (Müller et al., 1993) and moving (Doubrovine et al., 2012; O'Neill et al., 2005) hotspot frames, as well as the true-polar wander corrected (Steinberger and Torsvik, 2008) and subduction (van der Meer et al., 2010) reference frames. A detailed analysis of alternative absolute reference frames for the Seton et al. (2012) model was conducted by Shephard et al. (2012), and concluded that the hotspot reference frames provided the best reproduction of subduction-driven mantle structure at present-day. Due to the lack of preserved hotspot tracks for times before ~100-120 Ma, neither fixed nor moving hotspot reference frames can be used for the entire post-Pangea timeframe, thus justifying our use of a tested hybrid reference frame covering the 200 Myr model temporal extent.

Relative plate motions are linked back to an African plate circuit, except for the Pacific Plate, which cannot be linked to the Indo-Atlantic plate circuit for times before 83.5 Ma (Seton et al., 2012). The magnetic polarity reversal timescale of Cande and Kent (1995) is applied for times younger than the Late Cretaceous, and the timescale of Gradstein et al. (1994) is used for earlier times. The most reliable of 70,000 magnetic anomaly identifications form the basis of the Seton et al. (2012) plate motion model. The root mean square (RMS, v_{rms}) velocities are defined as

$$v_{rms} = \sqrt{\frac{v_1^2 + v_2^2 + v_3^2 + \cdots + v_n^2}{n}}$$

and n is the number of velocity sampling nodes belonging to the sample (Fig. S1, global or plate-specific). The plate identifier (Plate ID), time of plate reconstruction, perimeter and subduction zone lengths are tracked through time (Table S1). Continental RMS velocity and areas are recorded, as well as the area of Phanerozoic, Proterozoic and Archean lithosphere based on the tectonothermal ages modelled by Artemieva (2006). Although our plate motion model does not include continental deformation, conservative estimates of continental area are computed based on the union of all continental polygons. Continental regions included continental lithosphere as well as volcanically-modified oceanic crust and island arc terranes. However, more generally continental area is likely underestimated, especially in deforming regions, such as the India-Eurasia collision zone (van Hinsbergen et al., 2011a), and where continental lithosphere may have been lost to subduction.

The emplacement of young oceanic lithosphere at seafloor spreading centres is complemented by recycling of older lithosphere at subduction zones, resulting in lower portion of preserved lithosphere representing older spreading systems. Hence we limit our analysis to post-Pangea times where plate reconstructions are largely based on data and interpretations from preserved lithosphere. The area of preserved lithosphere during our model timeframe was computed as “World Uncertainty” following the method of Torsvik et al. (2010). It is important to note that this estimate is likely too conservative, as it does not include the reasonably well-constrained portions of the oceanic lithosphere where one flank of the spreading system is preserved (e.g., Pacific–Izanagi, Pacific–Farallon, Pacific–Kula and Pacific– Phoenix plate pairs) and can be used to resurrect the subducted flank based on an assumption of spreading symmetry. Although our plate reconstructions do not capture the entire history of plate tectonics, we apply a uniformitarian assumption that our plate reconstruction timeframe is at least representative of the Phanerozoic, and likely earlier times when modern plate tectonics operated.

The analyses of RMS plate velocities were categorised to isolate the effects of particular tectonic parameters (subduction zone lengths, continental areas, etc.), whose results and statistical measurements are summarised in Table 1. The results are presented in boxplots on which whisker lengths are 1.5 interquartile ranges (IQR), as well as scatterplots with samples colour-coded by model reconstruction time for the purpose of comparing to time-dependent “World Uncertainty” (Fig. 3C). Least squares (thick black lines) and robust (thick grey lines) regressions, as well as comparisons to the equivalent Stoddard and Abbott (1996) analysis using present-day measurements alone (dashed black lines) are plotted to highlight any correlation between the predictor (e.g., continental area, subduction zone lengths, etc.) and target (i.e., RMS plate velocity) variable. The robust regression helps mitigate the effect of outliers by iteratively applying a reweighting to the least squares fitting strategy. Correlation coefficients described in text are from the robust fitting method, unless otherwise stated.

3. Results

3.1 Present-day plate velocities

Our plate reconstructions reproduce present-day relative plate velocities in an Africa (Nubia) fixed frame of reference with respect to the GSRM-v2.1 (Fig. 1) geologically current plate velocities (Kreemer et al., 2014). In both measures, Australia and the Pacific have the highest relative velocities. However, notable differences between the predicted and measured plate velocities (Fig. 1C) of up to 2 cm/yr exist for the Philippine Sea Plate and the Nazca Plate. Unsurprisingly, it is difficult to incorporate the Philippine Sea Plate into the global plate circuit as it is largely isolated by subduction zones, and results in the observed mismatch in predicted and measured plate velocities. The discrepancy in plate velocities for the Nazca Plate result from our choice of relative plate motion parameters (i.e., relative to the Pacific Plate), where a finite rotation at 5 Ma does not capture the more recent deceleration of the Nazca Plate observed in velocities derived from 3.16 Myr averaged seafloor spreading histories (DeMets et al., 2010). Although the differences in Philippine Sea and Nazca plate velocities are notable, we expect that such errors are systematic and are likely drowned out by the much larger number of individual RMS plate velocity samples in our analysis.

3.2 Global plate and continental RMS velocities

Global plate and continental reconstructions were used to derive RMS velocities for the plates and continents through time (Fig. 2). Global RMS plate velocities have fluctuated between ~5 and 10 cm/yr (Fig. 3A), with notable peaks resulting from seafloor spreading pulses in the

Pacific and Indian/Tethyan oceans. The continental RMS velocities are typically ~3 cm/yr, with significant ~10-20 Myr excursions resulting from seafloor spreading pulses (i.e., India) and/or absolute reference frame characteristics (e.g., Africa peak at ~110-100 Ma). RMS plate velocities are approximately a factor of two to three times higher than the RMS continental velocities (e.g., since ~50 Ma), highlighting that continents are generally much slower than oceanic plates.

3.3 Global subduction lengths

Global subduction zone lengths fluctuate between ~53,000 and 63,000 km in our plate reconstructions for the Mesozoic and Cenozoic (Fig. 3B). Periods with high subduction zone lengths globally do not correlate with high RMS plate or continental velocities. However, it can be argued that major increases in RMS plate velocities follow major reductions in subduction zone lengths, such as the Pacific high velocities in the Cretaceous following the cessation of Mongol-Okhotsk subduction. Similarly, the cessation of subduction along east Gondwana/Antarctica in the Late Cretaceous is temporally correlated with an increase in global RMS plate velocities, suggesting that the convergence in the circum-Pacific was accommodated along the northern subduction zones rather than also along Gondwana. However, intra-Pacific subduction zones are poorly constrained, and more work is required to evaluate the effects of global subduction zones lengths on RMS plate velocities.

3.4 Effects of absolute reference frames

Plate velocities and plate boundaries are sensitive to the absolute reference frame used, as reviewed by Shephard et al. (2012). The choice of absolute reference frame accentuates existing peaks or troughs in the global plate RMS velocities (Fig. 4A), with the motion of Africa (the base of the rotation hierarchy) propagated across the rotation hierarchy. The global RMS plate velocities (Fig. 4A) vary significantly between the absolute reference frames for Late Cretaceous and early Paleogene times, with up to ~2 cm/yr RMS variations. The motion of Africa, as the base of the

Indo-Atlantic absolute reference frames, is expected to differ considerably between the different plate-mantle frames of reference (Fig. 4B). However, any accelerations of Africa are likely to propagate along the plate circuit, and be amplified on plates that move with Africa and are closer to the Euler equator of the plate rotation.

The RMS speed of Africa is ~1-3 cm/yr across the three reference frames since ~50 Ma, with higher variability during older times. Both the moving hotspot (O'Neill et al., 2005) and subduction (van der Meer et al., 2010) reference frames produce a pulse in Africa’s RMS velocity (~6-7 cm/yr) in the mid Cretaceous. The contemporaneous pulse in the subduction frame is expected as it is a longitudinal correction applied to the hybrid moving hotspot and True Polar Wander-corrected frame in the Seton et al. (2012) model. The fixed hotspot (Müller et al., 1993) and alternative moving hotspot (GMHRF, Doubrovine et al., 2012) reference frames suggest a peak (~4-6 cm/yr) in the Late Cretaceous instead, which does not exist in our hybrid reference frame. However, the mid Cretaceous acceleration is better correlated with a major global plate reorganization event (Matthews et al., 2012) and a number of LIP eruptions (i.e., proximal plume head arrivals) (Fig. 4B-C), although it is also the transition between the moving hotspot reference (O'Neill et al., 2005) to the TPW-corrected (Steinberger and Torsvik, 2008) reference frame.

The cascading effect of the absolute reference frames on India (e.g., mid Cretaceous, Fig. 4C), inheriting the absolute motion of Africa as well as the relative motion resulting from seafloor spreading, is overall less pronounced than the effect on Africa’s RMS plate velocities alone. Three major pulses in India’s motion occur at 132-124 Ma, 87-83 Ma and 68-52 Ma – reaching RMS plate velocities of ~15, 17-19 and 16-18 cm/yr, respectively. The significant plate accelerations in the RMS velocity plots are not likely to originate from the propagating effects of the absolute reference frame, but rather dominated by relative plate motions. However, the ~110-100 Ma peak in Africa’s RMS velocity can be identified in smaller peaks in the RMS velocities of India and other plates (see Discussion).

3.5 Subduction zone and continental effects on plate velocities

The effects of subducting portion plate perimeter on RMS plate velocities were analysed for the 200 Myr model timeframe (Fig. 5A) and confined to plates with any history of slab pull (i.e., actively being subducted), including the (proto-) Pacific plates, Australia (and Capricorn), India, the Meso/Neo-Tethyan plates, as well as the African and Arabian plates. The RMS plate velocities of all 3,952 samples over the model timeframe had a median value of 4.2 cm/yr (AP, Fig. 5). Plates with no subducting portion of their perimeter (NO-SZ, Fig. 5A) were the slowest of any category based on the median RMS velocities (2.6 cm/yr), followed by plates with less than 25% of their perimeter being actively subducted (L-SZ, Fig. 5A), with a median of 4.4 cm/yr. Plates that had any subducting portion of the perimeter (SZ) and plates with more than 25% subducting portion of their perimeter (H-SZ, Fig. 5A) had the highest RMS plate velocities (7.1 and 7.9 cm/yr median values, respectively) in this category, which is more than double the value for plates surrounded purely by transforms and/or spreading centres. Notably, more than 75% of the samples belonging to the fastest category (H-SZ, Fig. 5A) are beyond the IQR of the slowest plates in this category (NO-SZ, Fig. 5A), highlighting the dominance of subduction zones in driving plate motions (Forsyth and Uyeda, 1975).

The effect of continents on plate RMS velocity was compared to all plates, with the slowest plates (2.8 cm/yr median) having more than 50% of their area comprised of continental (i.e., non-oceanic) lithosphere (H-CT, Fig. 5B), and the fastest plates (8.1 cm/yr median) having a low portion of area comprising continental lithosphere (less than 25%, L-CT, Fig. 5B). Plates with 25-50% of their area as continent (M-CT, Fig. 5B) are also relatively slow, with a median RMS plate velocity of 3.8 cm/yr. There is a significant reduction in the maximum possible RMS plate velocity with increase in the absolute continental area (Fig. 6A), resulting in an inverse relationship that largely agrees with the findings of Stoddard and Abbott (1996), while achieving a correlation coefficient of -0.55. However, our regressions are systematically shifted upwards, indicating that plate velocities have been generally higher in the Mesozoic-Cenozoic than suggested by the present-day analysis of

Stoddard and Abbott (1996). The continental fraction of plate area is also negatively correlated with RMS plate velocities (Fig. 6B), yielding the best correlation coefficient of -0.77 of all analyses, even though visual scatter seems high. More fundamentally, plates with less than 50% continental area can generally attain maximum RMS plate velocities of ~20 cm/yr, while plates with more than 50% continental area can attain approximately half of the maximum RMS plate velocities (~10 cm/yr).

The combined effects of continental portion of plate area and the subducting percentage of plate circumference are significant (Fig. 5C), with plates that have less than 25% continental area and more than 20% subducting portion of their perimeter (L-CT, H-SZ) are the fastest plates of all categories (8.5 cm/yr median RMS velocities). Conversely, plates with more than 25% continental area and less than 20% subducting portion of their circumference are much slower (2.8 cm/yr median RMS velocities), but are only slightly faster than the slowest plates (NO-SZ in Fig. 5A, 2.6 cm/yr median RMS velocities).

For plates that have a history of slab pull, plates with higher subducting portions of circumference and lower portion of continental lithosphere (pink rectangle) tend to have the highest RMS plate velocities (Fig. 7). This suggests that even relatively small portions of subducting plate circumference may contribute to faster plate motions, whereas the effect of continental lithosphere is more gradual, but becomes dominant when continental lithosphere is greater than ~40% of total plate area (blue rectangle, Fig. 7).

3.6 Effect of cratons on plate velocities

Cratonic (Archean and Proterozoic) area is inversely related to the maximum plate RMS velocities attainable by plates in the Mesozoic-Cenozoic (Fig. 5D). Plates without cratons can reach maximum RMS velocities (22.7 cm/yr), with a median RMS velocity of 5.9 cm/yr. However, plates with more than 25% and 50% area covered by cratons are significantly slower, reaching maximum RMS velocities of 10.1 and 7.5 cm/yr, respectively. Their median RMS velocities are similar, with values of 2.8 cm/yr, suggesting that the presence of cratonic lithosphere within a plate is a significant limiting factor on plate velocities.

Both the absolute and fractional Archean cratonic areas have an inverse relationship with RMS plate velocities (Fig. 6C-D). However, the fractional Archean area is better correlated with RMS plate velocities (-0.54) than the absolute Archean area (-0.48). Our analysis (full black line) has a steeper negative slope than the findings of Stoddard and Abbott (1996), largely because we incorporate all plates through time and include plates that have no Archean cratonic portion (i.e., purely oceanic plates). The absolute and fractional areas of Proterozoic lithosphere (Fig. 8A-B) also have an inverse relationship with RMS plate velocities, but weaker (i.e., shallower slope of linear regression) than the effect of Archean cratonic lithosphere. Again, the Proterozoic fraction of plate area has a stronger negative correlation (-0.58) than the absolute area (-0.50) of Proterozoic lithosphere within a plate. Interestingly, the analysis of Stoddard and Abbott (1996) suggests that the increasing portion of Proterozoic lithosphere on a plate increases RMS plate velocities (dashed black line, Fig. 8B) using present-day data alone, and excluding the Australian Plate. However, our results indicate the opposite, even when considering present-day samples alone (Figure S5).

The combined Archean and Proterozoic areas also tend to have a limiting factor on RMS plate velocities, with a significant reduction in attainable plate velocities with increasing absolute and fractional areas of a plate (Fig. 8C-D). The effect related to absolute cratonic area is similarly observed by Stoddard and Abbott (1996), except that our regressions are again shifted upwards and have a shallower slope. In all analyses, the portion of plate area covered by continental, Archean cratonic or Proterozoic shield lithosphere plays a much stronger role (i.e., steeper regression slopes and stronger correlation) than their absolute area, suggesting that plates with a high portion of continental and cratonic lithosphere tend to be much slower than plates with high portions of purely oceanic lithosphere.

4. Discussion

Our time-dependent analysis suggests that the portion of continental (and cratonic) area significantly reduces RMS plate velocities, likely due to continental drag resisting plate motion as described by Forsyth and Uyeda (1975). In contrast, Stoddard and Abbott (1996) suggested that the increasing portion of Proterozoic lithosphere tends to increase the RMS plate velocities, as the Proterozoic shield root is embedded in a lower-viscosity asthenospheric layer, thus enabling faster plate motions. Our present-day and time-dependent analyses (Fig. S5, 8B) do not reproduce the results of Stoddard and Abbott (1996), and instead suggest that the Proterozoic portion of plate area is inversely correlated with RMS plate velocities. More generally, plates with large portions of continental lithosphere and smaller portions of subducting plate perimeter are the slowest, which is consistent with the present-day RMS plate velocities of Antarctica (1.1 cm/yr), Africa (2.0 cm/yr), North and South America (~2 cm/yr), and Eurasia (1.7 cm/yr). Conversely, plates with smaller portions of continental lithosphere and subducting portions of plate perimeter are considerably faster at present-day, such as the Pacific (7.9 cm/yr RMS) and Australia (5.7 cm/yr RMS).

4.1 Possible influence of plume head arrival

Although the present-day speed of North and South America is relatively slow, RMS plate velocities of North America reached ~7-8 cm/yr in the mid Cretaceous and Eocene times, while South America's RMS velocity reached ~5 cm/yr. The Paleogene pulse (~60 to 50 Ma) in RMS plate velocities for North America is correlated with a major pulse of plume activity in the North Atlantic, including peak magmatism during ~57-52 Ma on Greenland (Mjelde et al., 2008), as well as a pulse in Iceland plume activity during ~62-54 Ma (White and Lovell, 1997). As it is a short-lived acceleration (~10 Myr) of North America, it may be a transient effect of plume head arrival, as has been suggested for India's acceleration from ~65 Ma (Fig. 4C) in response to the Reunion plume head arrival (van Hinsbergen et al., 2011b). The earlier, and short-lived (~10 Myr), acceleration of the North American plate at ~100 Ma is more difficult to link directly to plume head arrival, however, a ~110-90 Ma regional unconformity in the North Atlantic (Japsen et al., 2007) has previously been linked to anomalously hot mantle and possible plume influence (Jones et al., 2001). Although the reconstructed position of the Iceland hotspot in the vicinity of Greenland (Lawver and Müller, 1994) is consistent with plume head arrival at ~100 Ma, linked to the mid Cretaceous Ellesmere Island volcanics, further testing using numerical geodynamic models is needed to assess whether plume head arrival can accelerate a large plate such as North America with a large portion of continent. Mechanisms that will require investigation include the role of asthenospheric lubrication, the maximum radial distance of plume effects, the excess gravitational potential from a rising plume head, as well as thermal weakening of the lithosphere. The effects of plume head arrival is likely amplified in the presence of contemporaneous and complementary far-field plate boundary forces, such as the rapid acceleration of India (reaching RMS plate velocities of ~18 cm/yr) resulting from the positive feedback created by plume head arrival from the south-west, largely northward slab pull from Tethyan subduction and a relatively larger area of oceanic portion of the plate. Our analyses suggest that continental and cratonic keels can encourage plate accelerations in the vicinity of plume head arrivals, suggesting a strong influence of asthenospheric flow (Stoddard and Abbott, 1996) and weakened lithosphere- asthenosphere coupling during plume-head arrival (van Hinsbergen et al., 2011b). However, in all other cases, the continental and cratonic keels tend to impede fast plate motions.

4.2 Anomalously rapid motions of large continents

Our findings that cratons restrict plate velocities disagree with a paleomagnetic case study indicating rapid motion of Laurentia and Baltica in the late Precambrian to early Paleozoic (Gurnis and Torsvik, 1994), suggesting minimum speeds of 23 cm/yr for large continental blocks, that have a large component of Archean lithosphere with deep continental keels. Continental RMS velocity analyses derived from paleomagnetic Apparent Polar Wander (APW) paths indicate significant variations in velocities, with values greater than ~20 cm/yr in the Archean, and with ~10 cm/yr maximum limits since the Mesoproterozoic (~1600 Ma) (Piper, 2013), similar to what we find for the Mesozoic and Cenozoic. Much larger RMS (plate or continental) velocities in the past may represent more vigorous mantle convection, and hence faster plate motions, from (~150-200°C) hotter mantle temperatures (Abbott et al., 1994). However, a paleomagnetic synthesis from continents suggests that plate velocities were slower in pre-Cambrian times than during the Phanerozoic (Condie et al., 2014).

For the rapid motions of Laurentia and Baltica in the late Precambrian and early Paleozoic, two scenarios may explain their behaviour in the context of our results. First, the plates that carried these continents may have been similar to India in the early Cenozoic where plume head arrival effects were complementary to the slab pull acting on the plate. However, if the rapidity of Laurentia and Baltica motion persisted for more than ~10 Myr, then the short-lived plume head arrival positive feedback is unlikely to explain long-lived and anomalously fast motions of large continents with deep cratonic keels. An alternative scenario, with prolonged rapid motion of Laurentia and Baltica may necessitate very large plates (with less than ~20% continental area, see Fig. 7) and high portions of subducting plate circumference. However, it is important to note that the rapid motions of Laurentia and Baltica have previously been disputed as artefacts (see Condie et al., 2014), and thus additional work is required to reconcile the long-term rapid motion of these large continental blocks that is not supported by our Mesozoic-Cenozoic analysis of plate and continental velocities.

4.3 The role of the asthenosphere

Our findings, as well as earlier studies, indicate that continental keels likely slow down plate motions. The mechanism for this has been previously described by Minster et al. (1974) as a thicker and more well-defined lower viscosity asthenosphere beneath oceanic plates than plates dominated by continental lithosphere, while “continental drag” forces were invoked by Forsyth and Uyeda (1975). The proposed thinner asthenosphere beneath continents resulting from thick keels strongly increases shear tractions from viscous drag (Conrad and Lithgow-Bertelloni, 2006; van Summeren et al., 2012), likely limiting plate motions to be similar to the underlying mantle flow. Numerical models of convection in a viscosity-layered mantle reproduce the observations that oceanic plates tend to move faster than continental regions, typically by a factor of three (Phillips and Bunge, 2005), similar to the RMS velocity trends we observe for all plates versus only continental regions (Fig. 3A). In addition, observed net rotation of the lithosphere with respect to the mantle is compatible with viscosity beneath oceanic lithosphere at least one order of magnitude lower than the viscosity of the asthenosphere beneath continents (Ricard et al., 1991), suggesting that purely oceanic plates are more decoupled from the underlying mantle than plates with deep continental keels (Becker, 2006). A common interpretation of such models is that deep continental keels impinge on the asthenospheric flow and increase the viscous coupling between mantle and lithosphere. However, in the case of plume head arrivals potentially causing short-lived accelerations of large continental and/or cratonic plates (e.g., India at ~65 Ma), the asthenosphere has also been invoked to play a crucial role (van Hinsbergen et al., 2011b) to reduce viscous coupling between the continental keel and underlying mantle flow.

4.4 Limitations of plate reconstructions

Plate reconstruction methods add an essential temporal component that captures plates and continental behaviour in post-Pangea times in order to alleviate the shortcomings of using present-day measurements. Our approach takes advantage of major improvements in plate tectonic reconstruction methods, as we utilise the time-dependent and continuously closing plate polygon algorithm described in Gurnis et al. (2012). This allows plate boundaries to move independently and create interlocking and time-dependent plate topologies, enabling automated and self-consistent sampling of plate geometries through time. The advantage of this approach is that the plate velocities can be sampled with high spatial resolution across the entire area of the plate, and obtain a better constraint on the range of velocities that depend on the size of the plate and its distance from the Euler pole. However, this assumes that our reconstructed plate boundaries and plate geometries are a true representation of the past. This shortcoming is best summarised by the "World Uncertainty" (Fig. 3C), which increases to ~60% by the time of the Pangea supercontinent at ~200 Ma, as a result of subduction and renewal of primarily oceanic lithosphere. It is most difficult to constrain the position of paleo- seafloor spreading centres and transforms in oceanic lithosphere that has now been subducted (such as the Meso/Neo-Tethys). In such cases, it would be beneficial to include constraints from anomalous volcanism, typically adakites (Thorkelson, 1996), that link slab tearing and slab window formation to ridge intersections with the subduction zone. Such an approach was used by Whittaker et al. (2007) to approximate the position of the Wharton Ridge on now-subducted oceanic lithosphere, with the resulting model incorporated in our plate reconstructions (Seton et al., 2012).

Although the reconstructed positions of seafloor spreading centres will require iterative improvement, our plate reconstructions attempt to fit multiple constraints to enforce plate boundary closure, which is a precondition for creating true plate tectonic reconstructions rather than "continental drift" scenarios. The reconstructed position of subduction zones is much better constrained than spreading centres or transforms as overriding continental blocks record arc volcanism, and hence the motion of the subduction zone can typically be linked to the overriding plate. Such an approach can be verified by linking geodynamic models to plate reconstructions in order to reproduce present-day mantle structure that can be validated using seismic tomography. Interpretations of subducted slab volumes have shown that alternative subduction scenarios can be tested (Van der Voo et al., 1999; Zahirovic et al., 2012), whilst also providing a possible absolute reference frame in the absence of reliable hotspot tracks in pre- mid-Cretaceous times (van der Meer et al., 2010).

Other aspects of the plate reconstructions that can be sources of error include uncertainties in the magnetic anomaly identifications, that both affect the velocities of plates, but also the plate geometries (such as the abandonment of a spreading centre). For example, the extinction of the Wharton Ridge in the Indian Ocean was interpreted to be at ~42 Ma based on the youngest identified magnetic anomaly (Krishna et al., 1995). However, additional marine magnetic anomaly identifications of reversals near the fossil ridge indicate a series of compressed younger anomalies, indicating that the Wharton Ridge was active until ~36 Ma (Jacob et al., 2014). Adding more detail from magnetic anomaly identifications is likely to improve plate reconstructions and flowline fits with fracture zones, but can add significant noise from compressed or dilated stages. Increasing magnetic anomaly identification resolution requires smoothing using new statistical techniques that assimilate acceptable limits on the torque variation rates inferred from detailed seafloor spreading histories (Iaffaldano et al., 2013). However, reconstructions for times during the Cretaceous Normal Superchron (CNS, ~121-83 Ma) remain a significant challenge in the absence of magnetic reversals from which plate motions can be estimated, thus requiring interpolated ages over a relatively long timeframe. Alternatively, plate reconstructions may need to incorporate robust and correlatable magnetic intensity fluctuations, rather than reversals, during the CNS (Granot et al., 2012), as well as additional absolute ages from ocean drilling programs.

The choice of a geomagnetic polarity reversal timescales can also lead to compressed or dilated seafloor spreading stages, leading to changes in seafloor spreading rates (Seton et al., 2009). However, these are systematic changes and are unlikely to change our results, but are worthy of evaluation in future work. Similarly, absolute reference frames tend to affect the motion of the base of the hierarchy (typically Africa), and thus propagate a systematic cascade of plate velocities down the rotation hierarchy. For example, the ~110-100 Ma acceleration of Africa is propagated to India, North America and Eurasia (Fig. 4C and 9A-B). Hotspot tracks provide the best absolute plate motion constraints (O'Neill et al., 2005; Shephard et al., 2012), but are largely lacking for times before ~100 Ma. As a result, a number of compromise absolute reference frames for earlier times are required either assuming plume fixity (Müller et al., 1993) or use comprehensive paleomagnetic datasets from which true polar wander is removed to isolate motions within the plate-mantle system (Steinberger and Torsvik, 2008). Testing alternative absolute reference frames using geodynamic models of subduction indicates that hotspot-based reference frames best reproduces present-day mantle structure (Shephard et al., 2012), consistent with our choice of absolute reference frames.

4.5 Implications of our findings

The relationships and guiding principles extracted from plate reconstructions of the Mesozoic and Cenozoic can be applied to constrain plate motions in pre-Pangea times using machine learning algorithms to help assess scenarios from a wide range of possibilities implied by geological and paleomagnetic constraints. Although reliable constraints and proxies for plate reconstructions become increasingly scarce deeper in geological time, it remains important to evaluate plate and continental reconstruction scenarios using post-Pangea tectonic principles, such as:

- fast plate motions (above ~10 cm/yr RMS) are more likely with high subducting portion of plate perimeter (above 20%) and low continental portion of plate area (below 20%),
- increasing continental and/or cratonic (Archean/Proterozoic) portions of total plate area tend to result in slower plate motions with plates with less than 50% of continental area have an RMS speed limit of ~20 cm/yr, while more than 50% continental area results in RMS speed limits of ~10 cm/yr, and
- plates with a significant portion of continental and/or cratonic area that exceed ~15 cm/yr RMS plate velocities for more than ~10 Myr should be flagged as possible plate reconstruction artefacts.

Further work should focus on assigning uncertainties based on confidences in the plate reconstruction – such as, whether it is based on well-constrained magnetic anomaly interpretations from oceanic crust, or whether aspects of the reconstruction for particular plates and times are less constrained and based on continental paleomagnetic or geological evidence. In addition, rigorous geodynamic modelling using realistic mantle and lithospheric rheologies is required to test the effects of continental keels, the role of the asthenosphere and that of plume head arrivals on plate velocities.

5. Conclusions

Our time-dependent analysis of plate speeds indicates that the slowest plates have no subducting portions of plate perimeter, while exhibiting large portions of continental plate area. Conversely, the fastest-moving plates have little continental lithosphere but larger subducting portions of plate circumference. The fraction of plate area composed of continental lithosphere, including Archean and/or Proterozoic cratons, significantly impedes fast plate motions. Global continental RMS velocities are typically ~3 cm/yr in the Mesozoic and Cenozoic, with significant departures with values of up to ~5-6 cm/yr during periods of rapid continental motion (such as India's acceleration at ~65 Ma). More generally, oceanic plates have typically 2-3 times higher RMS plate velocities than continental plates, which is reproduced by numerical models of mantle convection (Phillips and Bunge, 2005). The RMS plate velocity analyses highlight short-lived (~10 Myr) pulses of rapid motions of continental plates with deep keels, including India, Africa and North America, which are likely due to transient plume head arrival effects. In the case of India, complementary plume head arrival, ridge push and slab pull forces resulted in RMS plate velocities of ~16-18 cm/yr from ~65 to 55 Ma. However, although North America's motion has been suggested to result from flow in the upper mantle, it is much slower likely due to the increased shear traction from the cratonic keel into the slower-moving mantle return flow from Farallon subduction. Our analysis highlights the need to incorporate plate reconstructions when analysing factors controlling plate velocities, rather than depending on present-day measurements alone.

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Tables and Figures

Table 1. Statistical analysis of RMS plate velocities using our plate reconstruction approach, with results sorted in ascending order according to the median, which is less sensitive to outliers than the mean. Subducting portion (*) of plate perimeter means that part of the plate is subducting (i.e., likely contributing to slab pull), such as the Pacific Plate at present-day, but does not include plates that have subduction zones along their perimeter that do not contribute to slab pull (i.e., North and South America, ignoring the relative small contributions from the South Sandwich and Puerto Rico trenches). Statistical outliers are defined as samples beyond 1.5 IQR about the median. MAD, Median Absolute Deviation; IQR, Interquartile Range. See Tables S1-S2 Excel spreadsheets for raw data and additional statistics, respectively.

	Min	Max	Mean	**Median**	MAD	IQR	Sample Size	Outliers (%)
Plates with no subduction zone portion of perimeter	0.01	12.06	3.43	**2.59**	1.52	3.33	680	5.15
Less than 20% subducting portion and greater than 25% continental area*	0.33	7.44	3.15	**2.75**	0.91	2.39	250	0.40
Continental portion greater than 50% of plate area	1.03	7.85	3.18	**2.80**	0.79	1.99	258	3.88
Cratonic+Shield (Archean+Proterozoic) portion greater than 50% of plate area	0.06	7.47	3.08	**2.80**	1.17	2.39	371	0.27
Cratonic+Shield (Archean+Proterozoic) portion greater than 25% of plate area	0.06	10.12	3.25	**2.83**	1.03	2.29	1251	2.96
Plates with any cratonic/shield (Archean OR Proterozoic) portion of area	0.06	18.80	3.79	**3.16**	1.36	2.88	1852	4.64
Continental portion between 25 and 50% of plate area	0.33	18.70	4.21	**3.80**	1.61	3.28	143	0.70
All plates	0.01	22.72	5.14	**4.17**	2.17	4.83	3952	3.74
Subducting portion of plate perimeter is less than 25%*	0.33	18.47	4.99	**4.35**	2.39	4.75	581	3.96
Plates without any cratonic/shield (Archean OR Proterozoic) portion of area	0.01	22.72	6.34	**5.86**	2.96	5.91	2100	2.67
Plates with any subducting portion along perimeter	0.33	22.72	7.49	**7.05**	2.83	5.67	1161	2.84
Subducting portion of plate perimeter is greater than 25%*	1.61	22.72	8.86	**7.87**	2.14	4.69	718	5.85
Continental portion less than 25% of plate area	0.39	22.72	8.73	**8.13**	2.33	4.62	898	5.23
Greater than 20% subducting portion and less than 25% continental area*	1.25	22.72	9.70	**8.51**	2.25	5.53	672	1.04

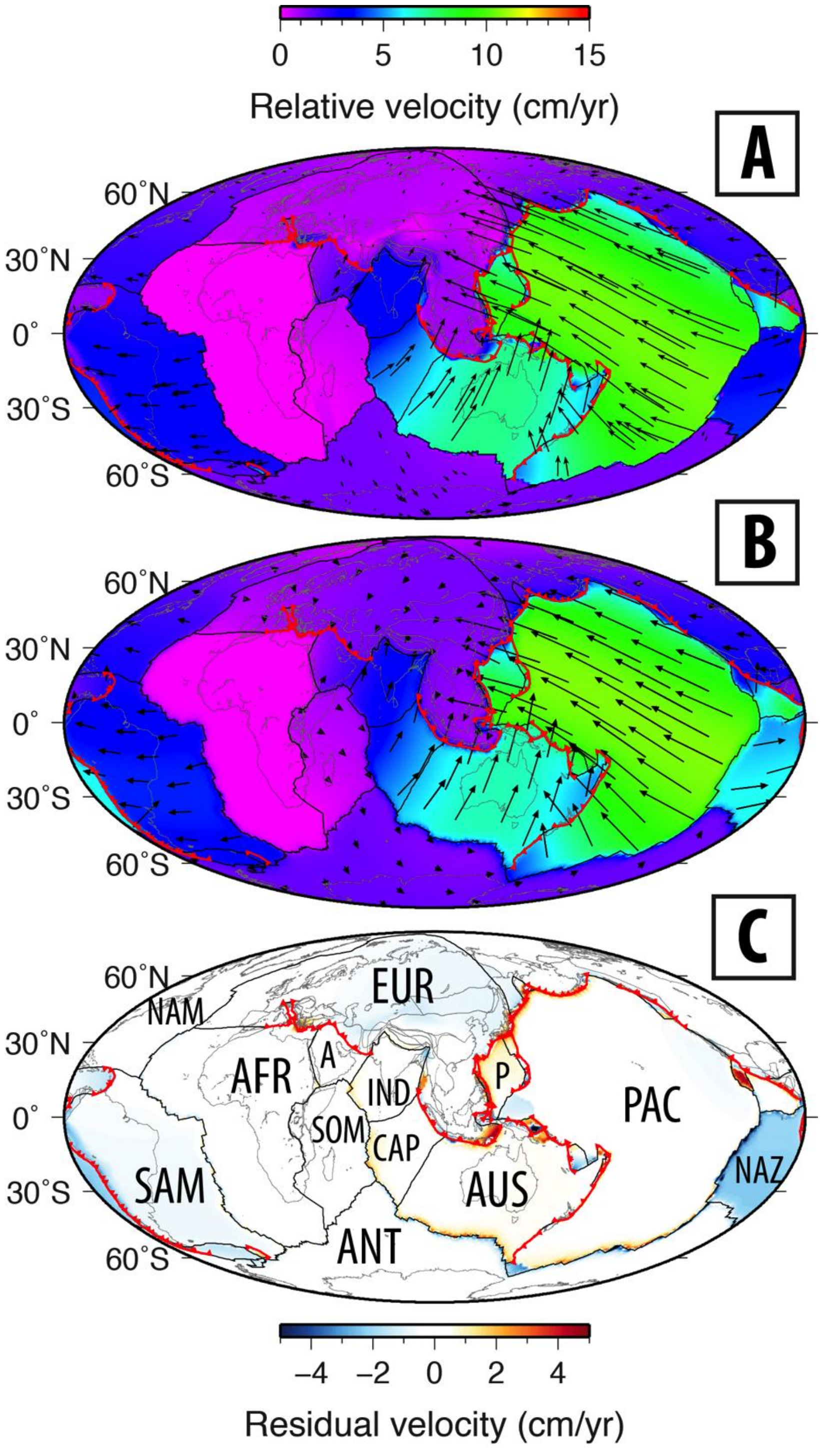

Fig. 1. A) Geologically-current velocities from GPS stations, Quaternary fault offset rates and youngest magnetic anomaly identifications in the oceans from GSRM-v2.1 (Kreemer et al., 2014) B) compared to the present-day plate velocities predicted by the (Seton et al., 2012) plate motion model with Africa (Nubia) fixed with plate boundaries (subduction zones: teethed lines, mid oceanic ridges/transforms: black lines), C) The residual (A-B) plate velocities highlight the differences resulting from the assumption of plate rigidity in the plate reconstruction (B), as well as artefacts near plate boundaries arising from slightly different plate boundary geometries. In addition, the Nazca (NAZ) and Philippine Sea (P) plates are up to 2 cm/yr different than the geologically current plate velocities. Major plate abbreviations: A, Arabian; ANT, Antarctic; AUS, Australian; CAP, Capricorn; EUR, Eurasian; IND, Indian; NAM, North American; NAZ, Nazca; SAM, South American; P, Philippine Sea; SOM, Somalian.

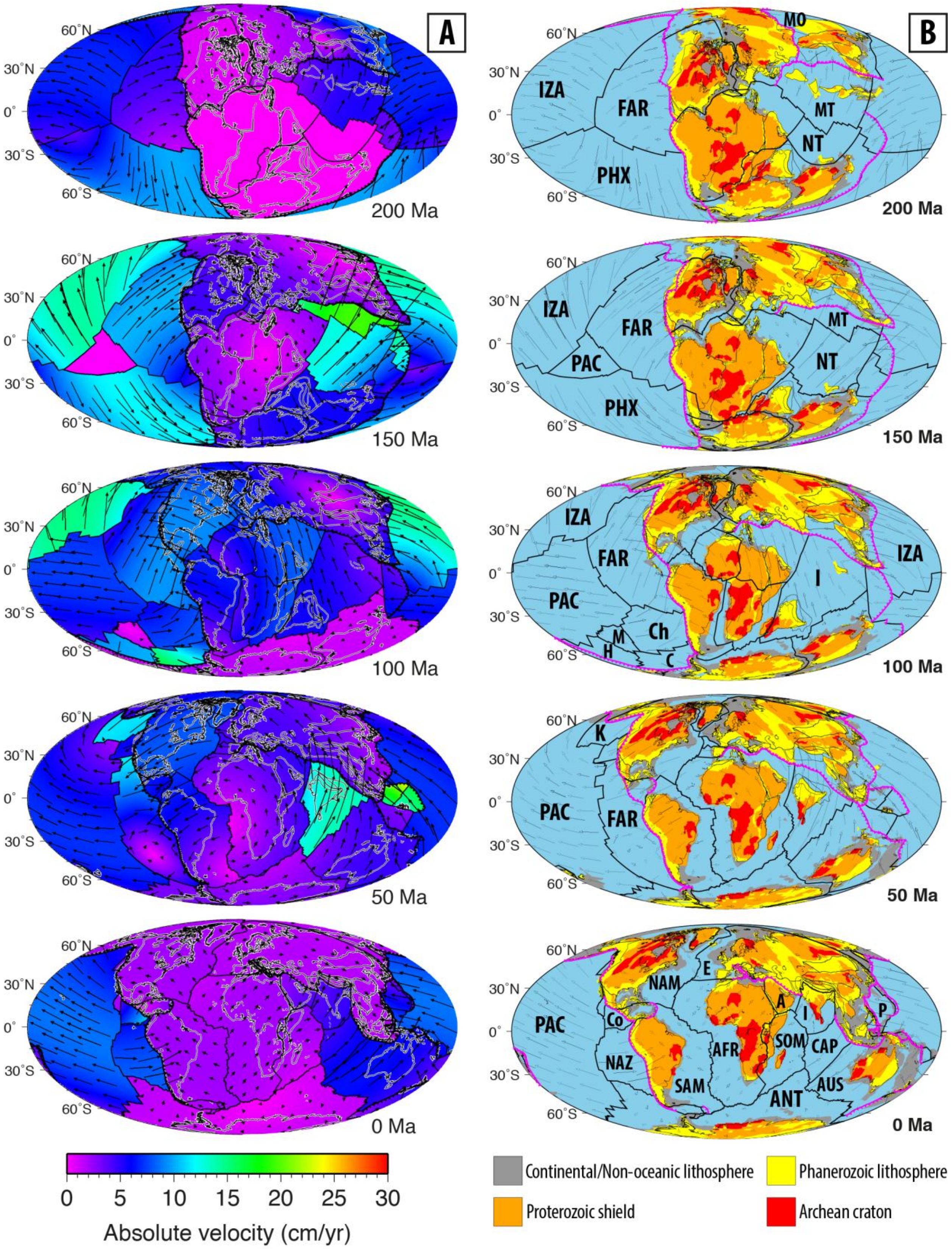

Fig. 2. A) Plate reconstructions with plate boundaries (black), present-day coastlines (white) and plate velocity vectors plotted on the velocity grid. B) The continental areas were calculated for each plate based on the reconstructed position of continental blocks, and the areas of cratonic elements were incorporated from the tectonothermal ages of Artemieva (2006). Animations in 1 Myr intervals of both velocity and continental reconstructions are provided in the Supplement. Major plates: A, Arabian; AFR, African; ANT, Antarctic; AUS, Australian; C, Catequil; Ch, Chazca; Co,

Cocos; E, Eurasian; FAR, Farallon; H, Hikurangi; I, Indian; I-A, Indo-Australian; IZA, Izanagi; J, Junction; K, Kula; M, Manihiki; MO, Mongol-Okhotsk; MT, MesoTethys; NT, NeoTethys; P, Philippine Sea; PAC, Pacific; PHX, Phoenix; SOM, Somalian.

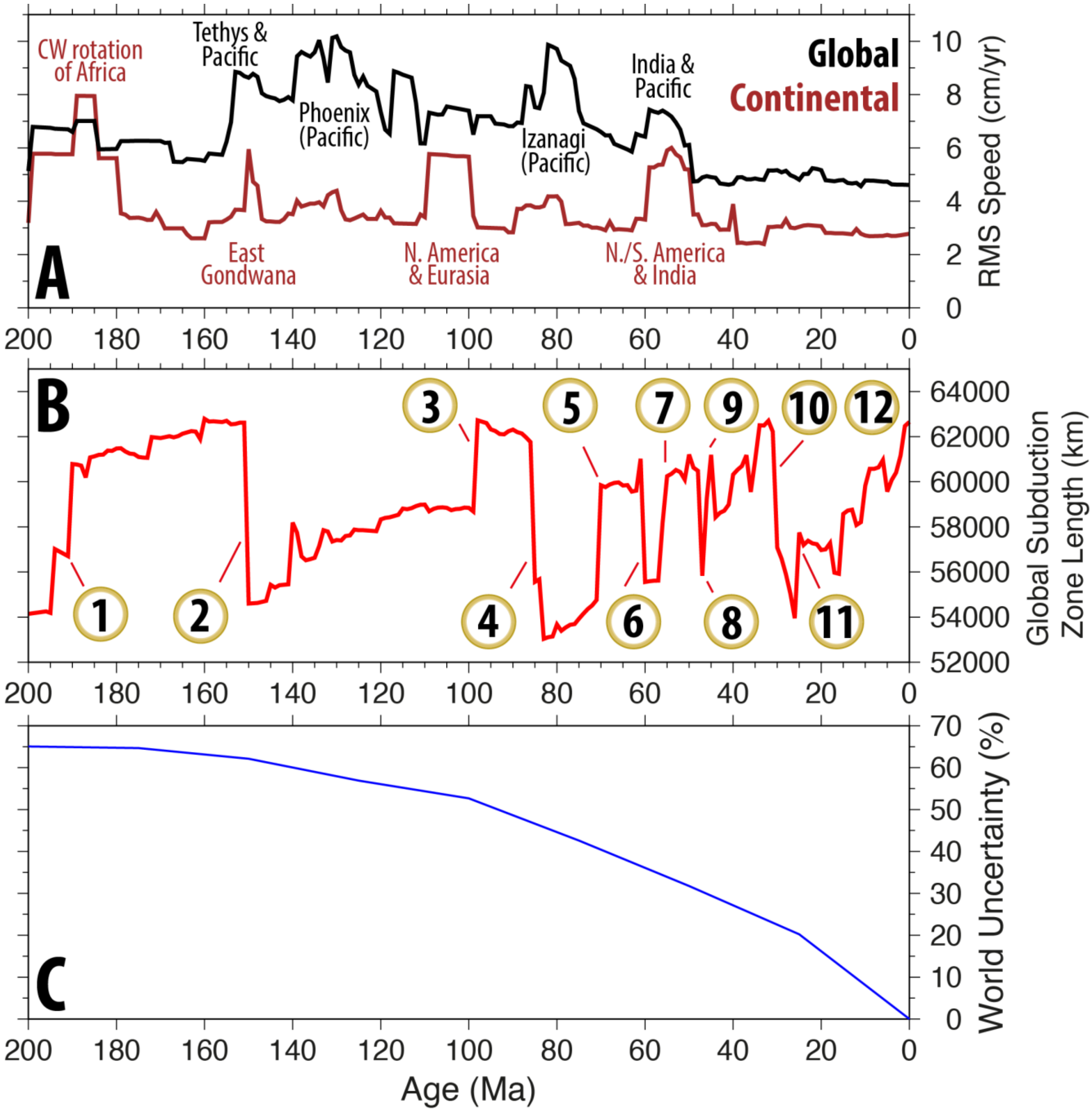

Fig. 3. A) Global plate (black) and continent-only (brown) RMS velocities. The continental curve represents the motion of continents alone, without the "oceanic" portion of the plate. This is useful for the comparison of pre-Pangea paleomagnetic-derived continental velocities. For alternative temporal resolutions, see Fig. S3. Plates and continents with large areas and/or high velocities dominate (labelled) elevated intervals of RMS speeds (see Fig. S3). B) Global subduction zone lengths in our plate reconstructions for the Mesozoic and Cenozoic. Major changes in subduction zone lengths are dominated by the following margins; 1, East Asia; 2, Mongol-Okhotsk; 3, East Pacific intra-oceanic; 4, Antarctic and East Pacific intra-oceanic; 5 and 6, Caribbean; 7, Philippine Sea Plate; 8, Junction; 9, SW Pacific; 10, India; 11, Macquarie; and 12, SE Asia and SW Pacific. C) World uncertainty in the modified Seton et al. (2012) model is derived from the area of preserved lithosphere following Torsvik et al. (2010).

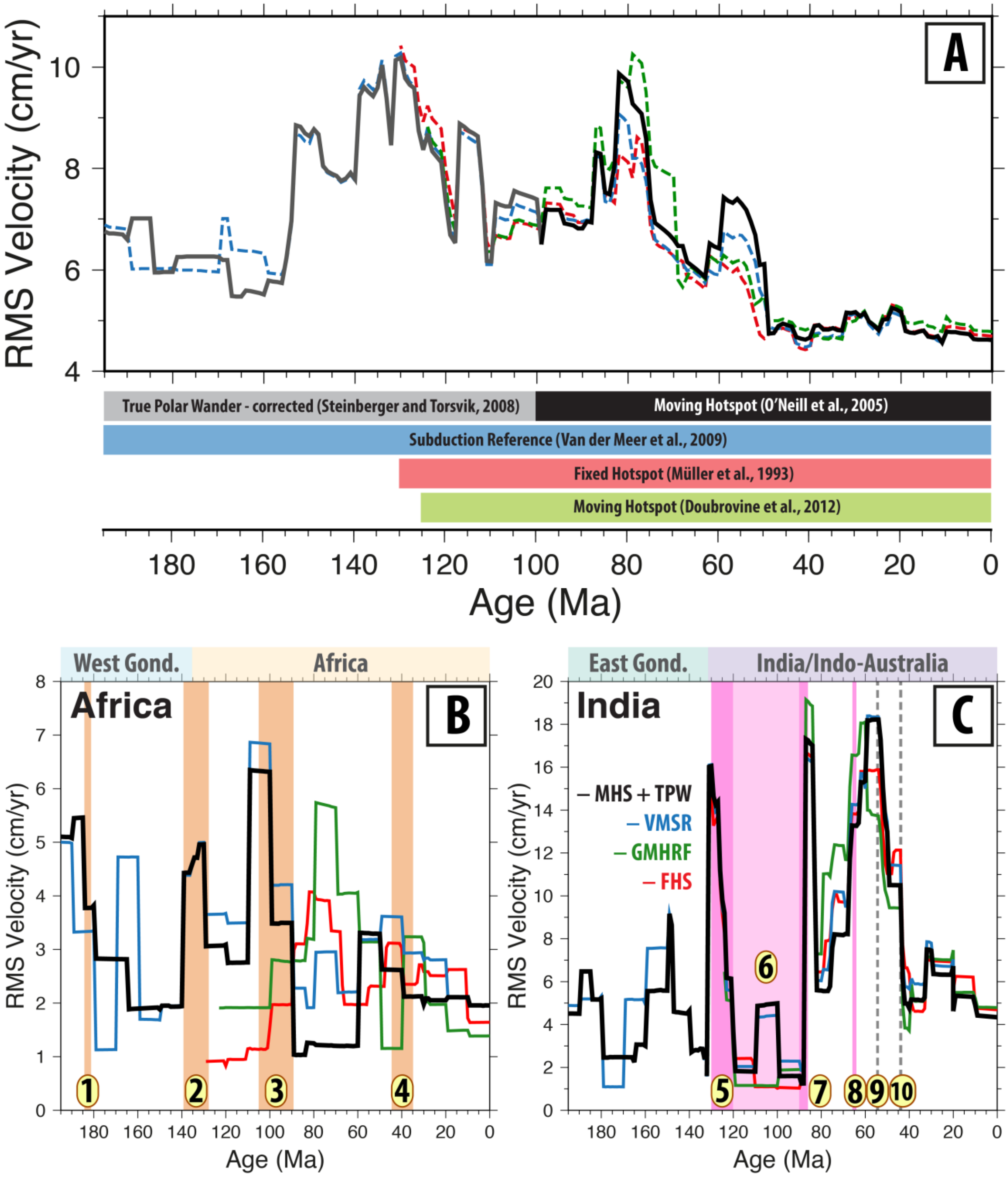

Fig. 4. A) Absolute reference frame effects on global plate RMS velocities. B) RMS plate velocities for Africa and C) India from the hybrid moving hotspot (MHS, O'Neill et al., 2005) and True Polar Wander-corrected (TPW, Steinberger and Torsvik, 2008) reference frame (black line) is compared to the fixed hotspot (FHS, Müller et al., 1993), global moving hotspot (GMHRF, Doubrovine et al., 2012) and subduction (VMSR, van der Meer et al., 2010) reference frames (red, green and blue lines, respectively). Many of the major changes in RMS plate velocities are spatio-temporally correlated with regional events, including the emplacement of 1) Karoo and Ferrar Traps, 2) Parana-Etendeka flood basalts, 3) Agulhas Plateau, 4) Afar and Lake Victoria, 5) Kerguelen plume head arrival resulting in Bunbury Basalts, 6) continued voluminous Kerguelen eruption, 7) Madagascar Traps, Morondava LIP, and 8) the short-lived but voluminous Deccan Traps. For India's motion, the RMS plate velocity drops significantly from ~18 cm/yr at ~55-52 Ma to values of ~11 cm/yr by 43 Ma (9-10), after which another major slowdown results in RMS velocities of

~4-6 cm/yr, and is related to the multi-phase India-Eurasia collision (Zahirovic et al., 2012). See Table S3 for Large Igneous Province references.

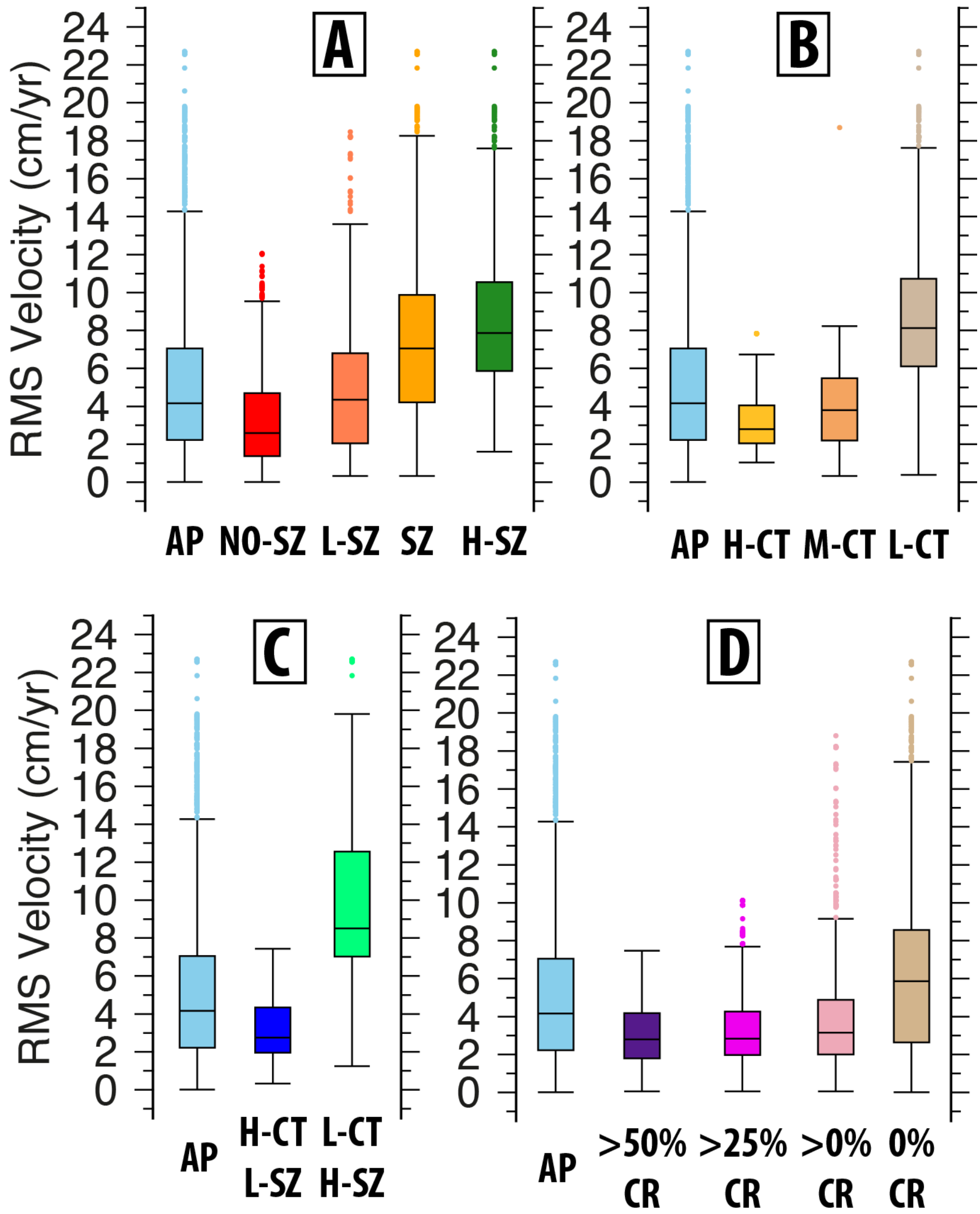

Fig. 5. A) RMS plate velocities of all plates (AP) compared to the RMS velocities of plates with varying portions of their perimeter being actively subducted. NO-SZ: Plates with no subducting portion of their perimeter, L-SZ: Plates with less than 25% of their perimeter being actively subducted, SZ: Plates that had any values (more than 0%) of subducting portion of the perimeter, and H-SZ: Plates with more than 25% subducting portion of their perimeter. B) The effect of continents on plate RMS velocity is compared to all plates (AP). H-CT: Plates with more than 50% of their area comprised of continental crust, M-CT: Plates with 25-50% of their area as continent, and L-CT: Plates with less than 25% continental area. C) Combined effects of continental portion of plate area and the percentage of plate circumference on RMS plate velocity. H-CT and L-SZ: Plates that have less than 25% continental area and more than 20% subducting portion of their perimeter. L-CT and H-SZ: Plates with more than 25% continental area and less than 20% subducting portion of their circumference. D) Craton (CR, Archean and Proterozoic) area is inversely proportional to RMS plate velocities.

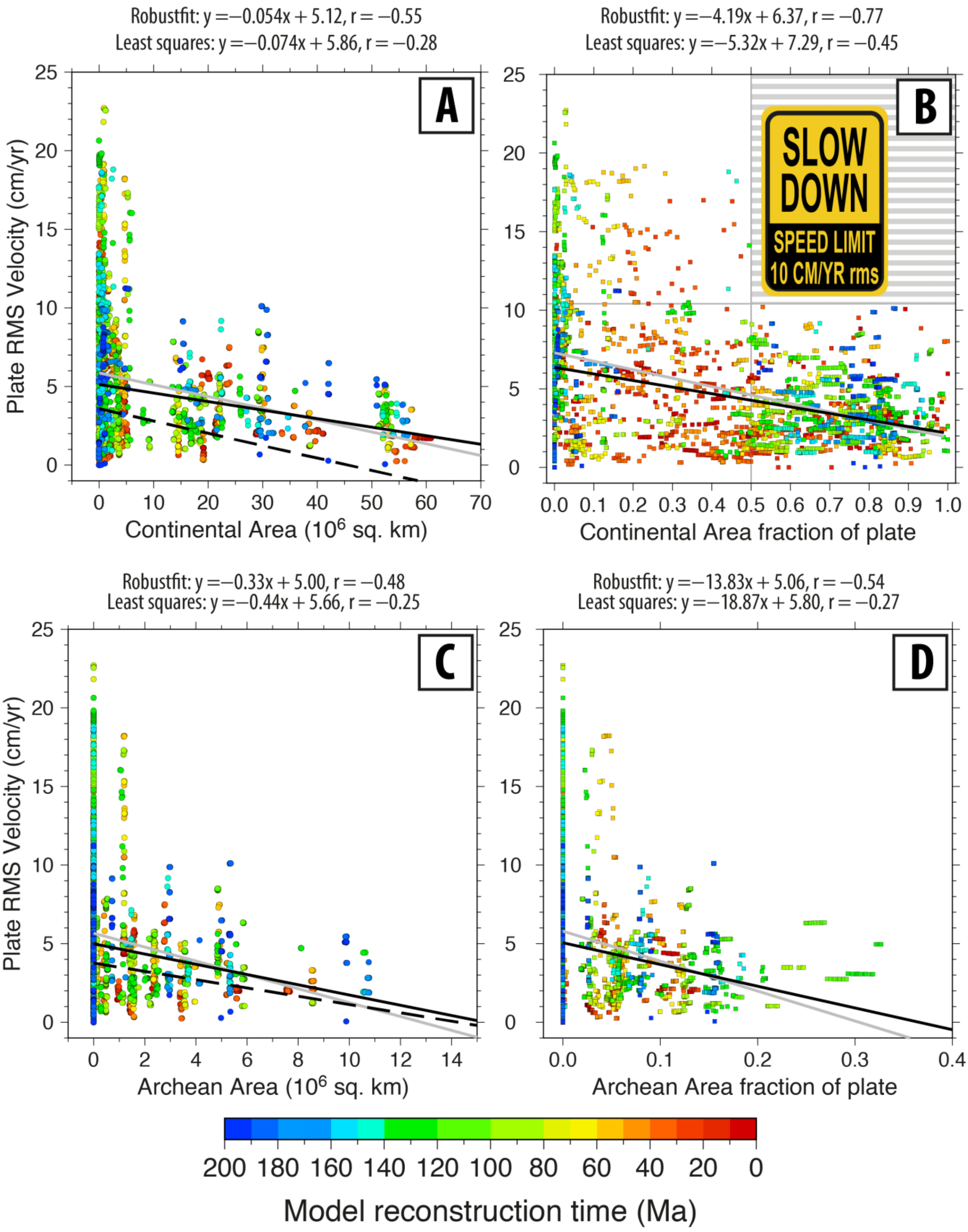

Fig. 6. Effect of absolute (A) and fractional (B) continental area on RMS plate velocities. Plates with more than 50% continental area do not exceed ~10 cm/yr RMS plate velocities (grey hatched rectangle). Absolute (C) and fractional (D) Archean lithospheric areas have an inverse relationship with RMS plate velocity. Robust linear regression (full black line), least squares linear regression (thick grey line), and linear regression from Stoddard and Abbott (1996) (dashed black line). Samples are coloured according to the reconstruction time in the plate motion model.

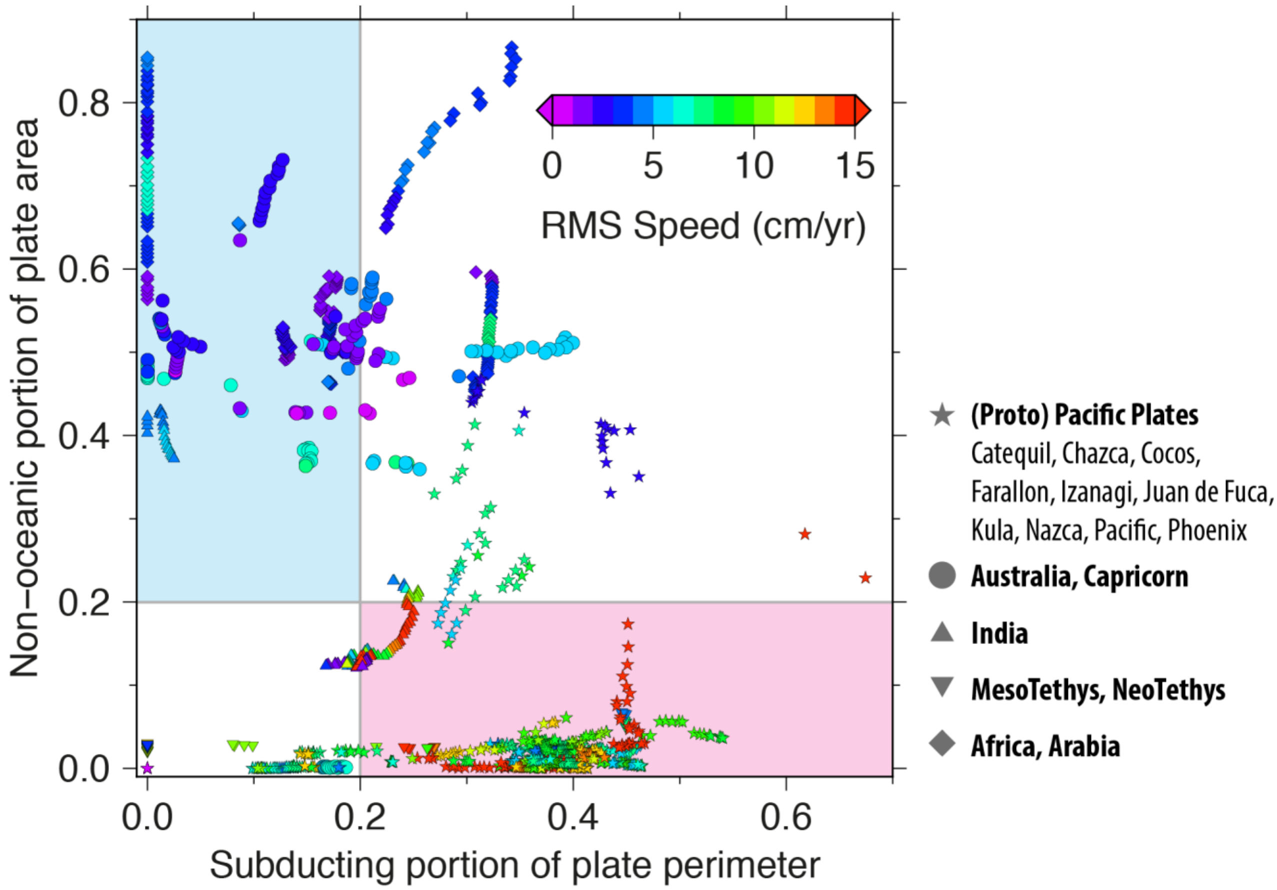

Fig. 7. Combined effects of subducting perimeter and continental (non-oceanic) portion of plate area on RMS plate velocities. Plates with more than 20% of subducting portion of perimeter and less than 20% continental area (pink rectangle) have significantly higher RMS plate velocities than plates with high continental areas and low subducting portions of plate perimeter (blue rectangle).

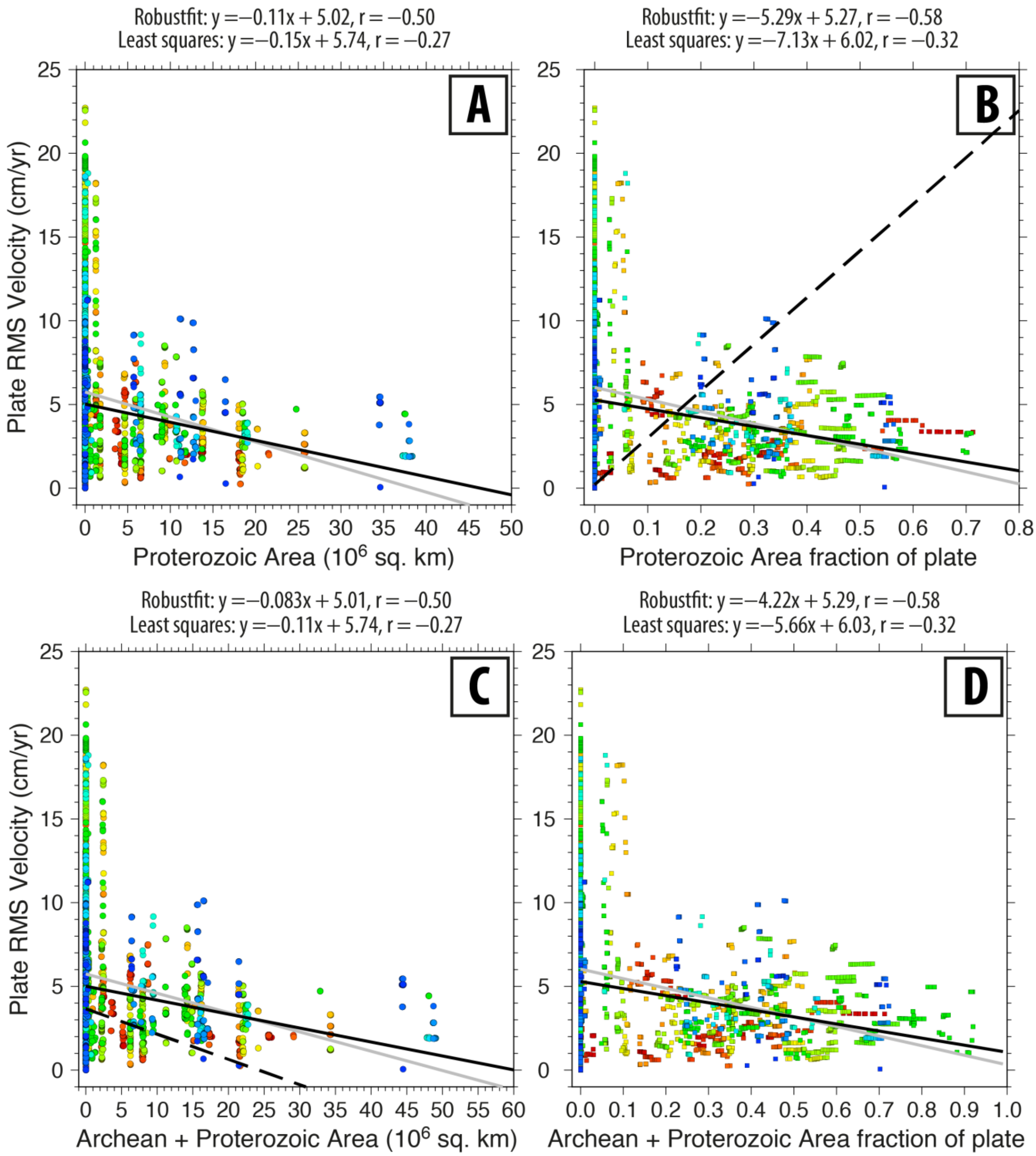

Fig. 8. The absolute (A) and fractional (B) areas of Proterozoic lithosphere also have an inverse relationship with RMS plate velocities. The effect of combined Archean and Proterozoic lithosphere absolute areas (C) and portions of cratonic plate area (D) on RMS plate velocities. See Fig. 6 for key to colours.

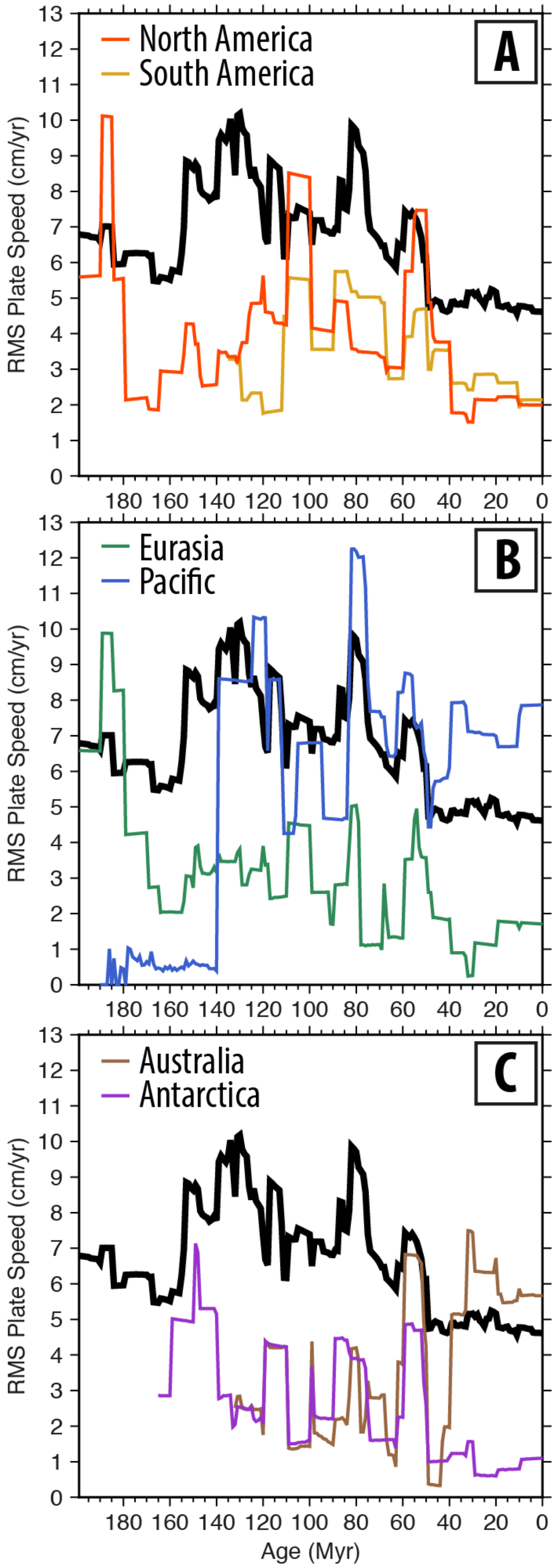

Fig. 9. Time-dependent RMS plate velocities for some major plates compared to the global RMS plate velocities (thick black line). RMS plate velocities for India and Africa are presented in Fig. 4B-C.

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